Non-Invasive Damage Detection, Location and Evaluation Technique Dedicated to Long Wind Turbine Blades

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Background

The survey of over 700 onshore WTs in Sweden during 1997 to 2005 indicates that rotor blades contribute 13.4% of WT failures, ahead of gearboxes (9.8%) and generators (5.5%); Another survey of 1,500 onshore WTs over 15 years suggests that rotor blades are responsible for 7% of WT failures, also ahead of gearboxes (4%) and generators (4%). As a consequence of these high failure rate figures, blade failures have become a primary cause of insurance claims. In American onshore wind market, they account for over 40% of claims, ahead of gearboxes (35%) and generators (10%). Blade failures are often associated with significant financial loss. For example, a sudden blade failure experienced by an onshore WT in Dunbar, Scotland in 2005 resulted in £1.25 million of repair cost and significant downtime. The figure would be even larger in offshore scenario due to site-accessing difficulties and the challenges of conducting blade repair/replacement over sea. Therefore, to improve the safe operation of WT blades is of importance to fulfil successful wind power generation. The work conducted in this research is to achieve such a purpose.

Methodology

Assume three blade sections $i-1$, i and $i+1$, with masses m_{i-1}, m_i and m_{i+1}, respectively. The sections $i-1$ and i are connected via stiffness $k_{i-1,i}$ and damping $c_{i-1,i}$; and the sections i and $i+1$ are connected via $k_{i,i+1}$ and $c_{i,i+1}$. Consequently, when an external load is applied to the blade, the dynamic response of the blade can be expressed as

$$\mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + \mathbf{K}\mathbf{X}(t) = \mathbf{F}(t)$$

It can be inferred that when a local defect occurs in section i, the values of $c_{i-1,i}$, $c_{i,i+1}$, $k_{i-1,i}$ and $k_{i,i+1}$ will change correspondingly; whilst the damping and stiffness in other blade sections may not change. This inspires the core thought of this research to develop a damage detection and location technique for WT blades by the approach of FRF transmissibility analysis. Since the corresponding values of damping and stiffness are dependent only on the structural integrity of the blade, the CM technique developed based on this idea will respond only to those changes caused by structural damage.

Assume when an external force $f(t)$ is applied to the blade, $x_i(t)$ and $x_k(t)$ $(t = t_0, t_1, \ldots, t_{N-1})$ are the data series measured by two neighboring sections. The frequency spectra of $f(t)$, $x_i(t)$ and $x_k(t)$ can be readily obtained by performing Discrete Fourier transforms (DFT)

$$\begin{cases} \mathcal{F}_f(j\omega) = \sum_{n=0}^{N-1} f(t_n) e^{-jn\omega/f_s} \\ \mathcal{F}_{x_i}(j\omega) = \sum_{n=0}^{N-1} x_i(t_n) e^{-jn\omega/f_s} \\ \mathcal{F}_{x_k}(j\omega) = \sum_{n=0}^{N-1} x_k(t_n) e^{-jn\omega/f_s} \end{cases}$$

Denote the FRFs of the i-th and k-th blade sections with respect to the external force $f(t)$ as $R_{x_i}(j\omega)$ and $R_{x_k}(j\omega)$, have

$$\begin{cases} \mathcal{F}_{x_i}(j\omega_r) = R_{x_i}(j\omega_r)\mathcal{F}_f(j\omega_r) \\ \mathcal{F}_{x_k}(j\omega_r) = R_{x_k}(j\omega_r)\mathcal{F}_f(j\omega_r) \end{cases}$$

the transmissibility of the FRFs at frequency ω_r can be described as

$$T_{i,k}(j\omega_r) = \frac{R_{x_i}(j\omega_r)}{R_{x_k}(j\omega_r)} = \frac{\mathcal{F}_{x_i}(j\omega_r)/\mathcal{F}_f(j\omega_r)}{\mathcal{F}_{x_k}(j\omega_r)/\mathcal{F}_f(j\omega_r)} = \frac{\mathcal{F}_{x_i}(j\omega_r)}{\mathcal{F}_{x_k}(j\omega_r)}$$

Use the transmissibility of the FRFs obtained when the blade has perfect structural integrity as benchmark, then a new CM criterion $C_{i,k}$ can be defined as

$$C_{i,k} = \frac{1}{N}\sum_{r=1}^{N}\left[T_{i,k}(j\omega_r) - T_{i,k}^{*}(j\omega_r)\right]$$

Verification Experiment

This technique was verified in the real fatigue test of a 45 m long WT blade. In the test, in total 9 FBG sensors and 6 accelerometers were installed along blade span to monitor the blade, see Fig.1. In the test, cracks initiated and propagated near sensors FBG5 and ACC3. The corresponding results are shown in Fig.2.

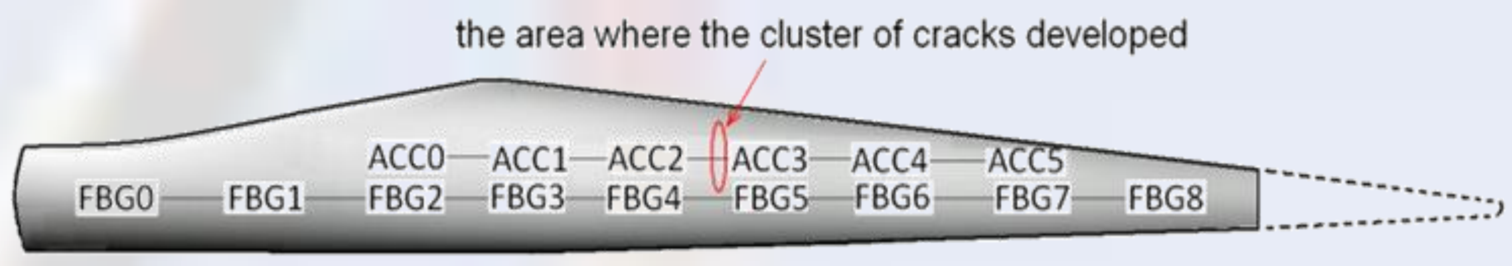
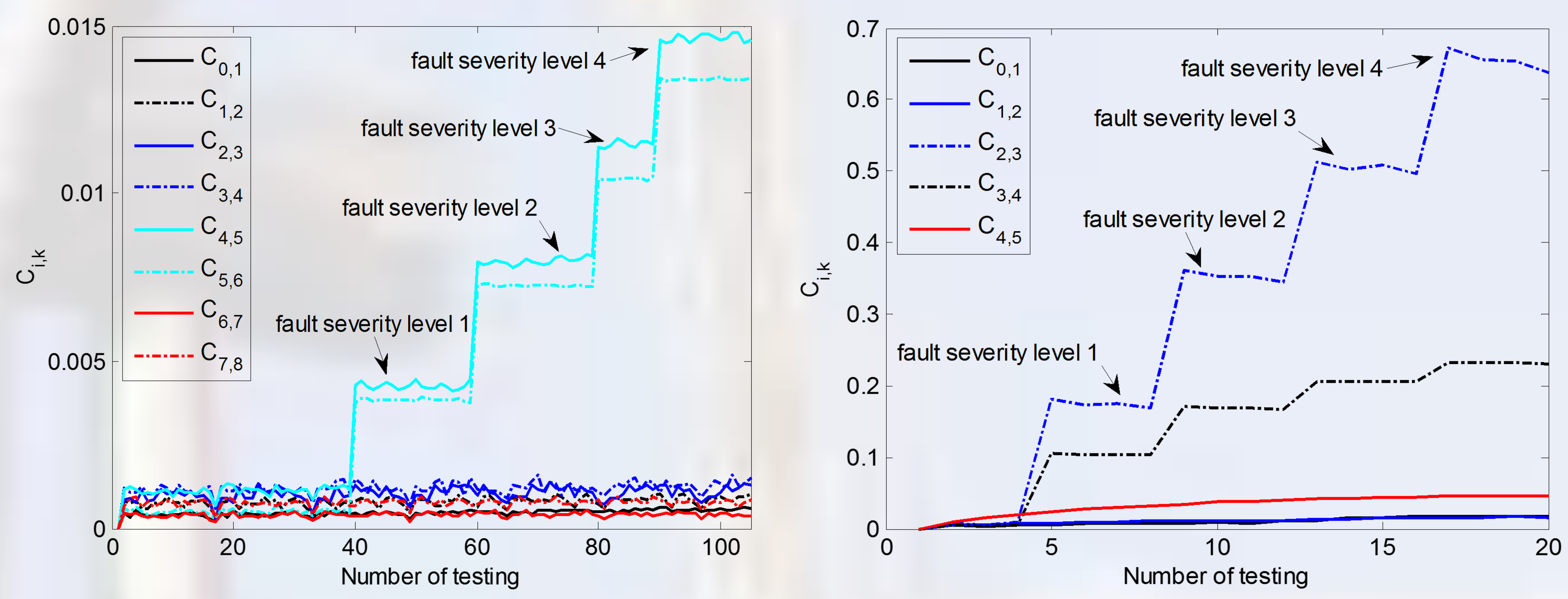


Fig.1 Transducers for verification test



(a) results from FBG strain gauges (b) results from accelerometers

Fig.2 Damage detection, location and evaluation

Future Site Application

In practical application, either an optic-fibre distributed strain sensor or a high resolution stereo imaging camera can be used to collect data. Both are in-situ data measurement techniques. The latter is shown in Fig.3.

Fig.3 Application of stereo imaging camera

Conclusions

1) The new technique will respond only to those changes caused by structural damage. Thanks to this merit of the technique, the false alarms due to load fluctuation and the ice/snow built up on blade surfaces can be fully avoided;

2) The new technique is effective not only in detecting the defects occurring in a blade but also in locating their positions and evaluating the severity of them.